A NEW APPROACH TO IONOSPHERIC DELAY CORRECTIONS IN SINGLE FREQUENCY GPS RECEIVERS

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Abstract

The IEN Time and Frequency Laboratory is equipped with single frequency GPS receivers to relate the Italian time scale to UTC and to give the traceability to the reference clocks of secondary laboratories. The synchronization data obtainable from the GPS system, in spite of its high performances, are affected by various error sources, one of the most important being the ionospheric corrections applied inside the receivers according to a model.

To evaluate the influence of these corrections on the common-view synchronization results, some investigations have been performed at IEN, using measurement from an ionosonde to test some ionospheric models, and the data supplied by two dual-frequency GPS receivers located at or nearby time and frequency laboratories. For each geodetic receiver and satellite tracked, the differential hardware delay was computed using an original approach developed at IROE.

The computed ionospheric delay corrections have subsequently been used to post-process a set of GPS common-view synchronization results between IEN-Italy and ROA-Spain and the uncertainty of the comparisons evaluated.

INTRODUCTION

The comparisons between the reference clocks maintained in timekeeping laboratories are based worldwide on the GPS signals reception using the common-view technique according to the BIPM schedule. The increased accuracy and stability of the new commercial cesium clocks and of the primary frequency standards require an improvement in the uncertainty of the synchronization links.

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One of the most limiting factors in achieving this goal with the equipment actually in use is related to the ionospheric correction model adopted in the one-channel, single frequency GPS receivers, normally operated in the timing centers.
In this way it is difficult in fact to have a correct estimate of the delay affecting the GPS signals crossing the ionized part of the atmosphere, i.e. the ionosphere (about 100 to 1000 km in height) and the plasmasphere (beyond 1000 km).
A single-frequency GPS receiver is being used at IEN to synchronize the atomic clocks with those of other laboratories when a GPS satellite is visible in common-view. Measuring clock differences versus GPS time, a slight residual error of the order of nanoseconds, mostly due to the ionospheric time-delay, can be present.
Having the capability to access a data base of RINEX (Receiver INdependent EXchange) files, where the pseudorange, carrier phase data and navigation messages provided by dual-frequency GPS receivers of the Italian Geodetic Network, located in Torino and Rome, and by the Royal Observatory of San Fernando (Spain) are available, the following topics have been investigated and operations performed:

- some existing models for the computation of the *TEC* (Total Electron Content), in the direction of the satellites tracked, using the data obtained by an ionosonde and by a dual frequency geodetic receiver, both located at the ING (Istituto Nazionale di Geofisica) in Roma, have been compared;
- a computer program has been developed to get the ionospheric delay from the geodetic receivers data, requiring that the hardware delay only be supplied by an external source;
- the differential hardware delays of the satellites L1 and L2 carrier frequencies and of the dual-frequency GPS receivers, used to measure the ionospheric propagation delays (in Torino and San Fernando), to be substituted in the common-view differences, have been computed at IROE with a software that will be described in the followings;
- the improvement achievable, substituting the ionospheric corrections obtained from the previous technique over a ten days sample of GPS data files supplied by the single frequency receivers of IEN and ROA, have been checked versus the time scale differences computed using the standard common-view data.

MEASURING THE IONOSPHERIC DELAYS WITH GPS

The computer program realized, aiming to reduce the uncertainty contribution of the ionosphere on the GPS synchronization data as described later on, has allowed to compare the ionospheric delay measurements coming from a dual-frequency GPS receiver with those obtained from three ionospheric models. These models are the IRI-90 [1], the DGR (Di Giovanni, Radicella) [2] and a third model obtained by reconstructing the ionospheric electron density profile on the basis of a virtual profile from ionograms, provided by an ionosonde, for lower ionosphere, and from the DGR model for the topside of the ionosphere [3].
The DGR model is based on few particular points, critical frequencies and corresponding heights, in the ionogram that become fixed points for some mathematical functions approximating the electron density profile. This model was chosen because developed for the geographical site of the ionosonde (Rome).

The IRI-90 (International Reference Ionosphere) is the most common model describing the ionosphere for geomagnetically quiet conditions. This model uses the longest series of data that is the basis for electron density profile computations. The input parameters for the three models have been obtained from ionograms given every five minutes by one of the ING ionosondes.
The three models provide an evaluation of the vertical *TEC* (Total Electron Content), measured in *TEC* units (10^{16} electrons/meter^2). This evaluation has been slanted in the direction towards GPS satellites.
The ionospheric time-delay for a signal at frequency f is bound to *TEC* along the signal path as follows:

$$\Delta t_{ion} = \frac{40.3}{c \cdot f^2} \cdot TEC \qquad [\mathrm{s}] \tag{1}$$

For the GPS L1 carrier (1.57442 GHz), 1 *TEC* unit corresponds to 0.54 ns of ionospheric time delay. In any case, all the three models provide an evaluation of the real ionospheric *TEC* and they don't consider the plasmasphere. In accordance with the results obtained by Ciraolo and Spalla at IROE [4], it has been assumed that the plasmaspheric contribution is (3 ± 1) *TEC* units without either daily or seasonal perceptible variability. Therefore 3 *TEC* units have been added to the evaluations of *TEC* obtained by the three models in order to include plasmasphere.
In Fig.1 dataareshown regarding satellites PRN03 and PRN15, observed in Rome on 23 June 1996. The solid curve is provided by the geodetic receiver of ING, the dashed one represents DGR data, the dash-dot one IRI-90 data and the dotted one is relative to the third model.
Taking into account the azimuth of the satellites, it can be observed that satellites to the north and mostly to the northwest direction show almost always overestimated measurements of ionospheric time delay according to the three models with respect to GPS measurements. On the contrary, satellites to the south usually show subestimated measurements of the ionospheric delay. Satellites to the west and especially to the east show minimal differences between models and GPS measurements.
To have an idea about the magnitude of the differences between the GPS and models results, the mean $\bar{e}$ of the absolute value of these differences and the standard deviation σ_e have been computed both for the daily values and for the whole period of observation and are shown in Table 1.

Date	DGR		IRI-90		Third model	
	$\bar{e}$	σ_e	$\bar{e}$	σ_e	$\bar{e}$	σ_e
1996/06/19	16	11	14	10	24	16
1996/06/20	14	10	13	9	26	17
1996/06/22	13	13	12	11	21	16
1996/06/23	13	10	12	8	23	15
Global	14	11	13	10	24	17

Table 1 - Differences of GPS dual frequency data versus ionospheric models in *TEC* units

Evaluations performed with the ionospheric models are not satisfactory because of several approximations passing from vertical to slant *TEC*, and of the presence of a persistent E sporadic layer not allowing for a precise acquisition of input data for models.

Due to the dispersive features in frequency of the ionosphere, using the L1 and L2 GPS carriers, one can evaluate the ionospheric delay. For both carriers (L1=1.57442 GHz and L2=1.22760 GHz) the GPS receivers measure, usually every 30 seconds, pseudoranges R_1, R_2 and carrier phases ϕ_1, ϕ_2. Pseudoranges are very noisy measurements both because of their nature and of the intentional errors in GPS (Selective Availability and Anti Spoofing [3]). The problem with carrier phase measurements is the carrier cycle ambiguity; that is the number of full cycles along the line of sight between the satellite and receiver is initially unknown.

Pseudoranges R_i for Li (i=1 or 2) carrier can be modelled as:

$$R_i = \rho + c\Delta\delta + \Delta R_{i,ion} + \Delta R_{tro} \quad [\mathrm{m}] \tag{2}$$

where ρ is the true distance receiver-satellite, c is the light speed, $\Delta\delta$ is the bias between satellite atomic clock and the receiver clock, $\Delta R_{i,ion}$ is the ionospheric delay in range units, and ΔR_{tro} is the tropospheric delay.

Carrier phases ϕ_i can be modelled in range units also as:

$$\lambda_i \Phi_i = \rho + \lambda_i N_i + c\Delta\delta - \Delta R_{i,ion} + \Delta R_{tro} \quad [\mathrm{m}] \tag{3}$$

where λ_i is the carrier wavelength and N_i is the carrier cycle ambiguity. The minus sign in the ionospheric delay is due to the different sign in the ionospheric group or phase refractive index.

In pseudorange measurements, $\Delta R_{i,ion}$ is the only term depending on the signal frequency; so one can write:

$$\begin{aligned} \rho &= R_1 - \Delta_{1,ion} \\ \rho &= R_2 - \Delta_{2,ion} \end{aligned} \tag{4}$$

and using (1) it is easy to deduce:

$$\Delta R_{i,ion} = \frac{R_1 - R_2}{1 - f_1^2/f_2^2} \quad [\mathrm{m}] \tag{5}$$

Following a similar procedure for the carrier phase we obtain:

$$\Delta\Phi_{1,ion} = \frac{f_2^2}{f_2^2 - f_1^2}\left[\Phi_1 - N_1 - \frac{f_1}{f_2}(\Phi_2 - N_2)\right] \quad [\mathrm{cycles}] \tag{6}$$

where the problem is that N_1 and N_2 are unknown.

But if N_1 and N_2 are neglected and the values obtained by (6) are subtracted from the first good datum, an extremely precise measurement of ionospheric delay variability is obtained. The first good datum is the one acquired when the satellite is for the first time above 30° minimum elevation. Subtracting this variability from (5), the data obtained are constant except for the noise which is presumably at null average value. So working out the average of these data, its noise is removed and

the "ionospheric offset" is obtained. Finally, the variability worked out using carrier phase is added to this offset.

For PRN03 satellite received in Roma on 23 of June 1996, one can see in Fig. 2 the difference in measurement precision of the ionospheric time-delay in *TEC* units using only the pseudoranges (segmented line) or the algorithm described above.

As a matter of fact many problems have to be solved in order to reach the most demanding levels of uncertainty needed by timing centers. The most relevant items are the cycle slips, that can occur when the GPS signal is lost for sometime and then tracked back again, and the hardware differential delays. As regards to the cycle slips, an automatic procedure for detecting and correcting the results, based on data taken before the occurrence of phase steps, has been developed and tested succesfully [5].

HARDWARE DELAY EVALUATION

The problem of the hardware differential delays or biases, due to the fact that the coded signals passing through different satellite and receiver hardware are subject to different delays for the two carriers, has been solved making the following assumptions:

- the observed DGD (Differential Group Delay), equivalent to the differential pseudorange (5) but expressed in *TEC* units, is written in terms of the slant *TEC* from the station to the satellite and the hardware bias β as:

$$DGD = TEC + \beta \tag{7}$$

- the ionosphere is an infinitesimally thick spherical slab, concentric to the Earth, located at an height of 400 km. The intersection point between the ionosphere and the satellite to station ray path is defined as the ionospheric point P as shown in Fig.3.
- given the vertical electron content *VEC* in P, *TEC* is written as:

$$TEC = VEC \cdot \sec \chi \tag{8}$$

where χ is the angle between the ray path and the vertical in P.

Each observation to the s-th satellite, referring to a specific ionospheric point P of known latitude Φ_S and longitude Λ_S, at a station time t, becomes:

$$DGD_s(t) = VEC(t, \Lambda_s, \Phi_s) \cdot \sec \chi_s(t) + \beta_s \tag{9}$$

Assumption of a model able to map $VEC(t, \Lambda_S, F_S)$ as a function of a set of coefficients makes it possible to write a set of equations of observation in terms of the unknown model coefficients and the biases β.

Several methods have been proposed to perform this, from the global multistation approach [6] to the simple single-station one used in this work, which is a development of the technique presented in [7]. In this approach it is assumed that the dependence of *VEC* versus latitude is linear, while time-longitude dependence occurs only through the local time $LT=t+\Lambda$ (in coherent units). *VEC* around the station, at a given time $t_S{}^*$, can be written, introducing the latitudinal slope of *VEC*, $m(t)$, as:

$$VEC(t_s^*, \Lambda_s, \Phi_s) = VEC(t) + m(t) \cdot (\Phi_s - \Phi_{sta}) \tag{10}$$

where *VEC(t)* is the vertical *TEC* at the station taken at a time *t* to which the same local time of the ionospheric point: $t_s{}^* + \Lambda_s = t + \Lambda_{sta}$.
Using (9) and (10), one can write *VEC* relative to the station at some time *t*:

$$VEC(t, \Lambda_{sta}, \Phi_{sta}) = [DGD_s(t_s^*) - \beta_s)]\cos\chi_s(t_s^*) - m[\Phi_s(t_s^*) - \Phi_{sta}] \tag{11}$$

Due to the global performance of GPS, the presence at any time *t* of at least four satellites (generally up to 7-8) over the horizon of the station, provides a corresponding number of DGD observations, not only at time *t*, but also at $t_s{}^*$. This enables comparison through (11) the estimations of the same $VEC(t, \Lambda_{sta}, \Phi_{sta})$ inferred by satellite s and r, namely:

$$[DGD_s(t_s^*) - \beta_s)]\cos\chi_s(t_s^*) - m(t_s^*)[\Phi_s(t_s^*) - \Phi_{sta}] = [DGD_t(t_r^*) - \beta_r)]\cos\chi_t(t_r^*) - m(t_s^*)[\Phi_r(t_t^*) - \Phi_{sta}] \tag{12}$$

For each epoch of observation, all the possible pairs of (12) are written. Moving the terms containing the unknowns on the left and the known terms on the right provides a set of linear equations of condition in the unknown β_s and the latitudinal slopes *m(t)*, which in matrix form is written as:

$$\mathbf{B}\vec{\beta} + \mathbf{M}\vec{\mu} = \vec{\varepsilon} \tag{13}$$

where $\vec{\beta}$ is the vector of the unknown satellite plus receiver biases, and $\vec{\mu}$ the one of unknown latitudinal slope; vector $\vec{\varepsilon}$ accounts for errors (noise, multipath) and model inadequacy. **B** and **M** are the coefficients of the unknowns as computed by (11).
The steps needed for the solution are described in the followings:
- differential phase and group delays are computed from the RINEX observation file smoothing the differential data over 10 minutes;
- navigation files containing the orbital data of GPS satellites are used to compute the satellite position, from which the ionospheric point and all the geometrical quantities involved can be obtained;
- according to (11), observations relative to the ionospheric points having the same local time are paired to build up the system (13).

The Least Squares solution is performed through successive approximations starting from null latitudinal slopes. No elevation mask is a priori used: low elevation points are automatically rejected, if needed, during the process of discarding the outliers. The internal consistency of the method results in better than one *TEC* unit; the accuracy is limited to 2-3 *TEC* units by the dynamics of the ionosphere and, sometimes more severely, by the effects of multipath.

POSTPROCESSING OF GPS COMMON-VIEW DATA

With the computer programs described before, the ionospheric corrections for two sites, Torino and San Fernando, where the national time scales of Italy and Spain are maintained and both single-frequency and dual-frequency GPS receivers are operated, have been determined. The geodetic receivers available were namely a Trimble 4000 SSI at the Politecnico di Torino (45°03'48" N,

07°39'41" E, 311 m height) and a Trimble 4000 SSE at the Real Instituto y Observatorio de la Armada in San Fernando (36°27'52" N, 06°12'20" W, 86 m height). The single-frequency receivers used for the measurements in common-view at IEN and ROA are an NBS/GPS and an AOA TTR6 respectively.

For eleven days, starting from 13 February 1997, for each satellite tracked by the geodetic receivers and included in the BIPM common-view schedule, the ionospheric corrections have been computed using the information in RINEX files, and the results have been used to correct the synchronization results obtained from the straight use of the single frequency receiver output data.

The curves for the two cases, reported in Fig.4, were obtained computing a daily mean value at 0h UTC of the difference between the two time scales by means of a linear regression over about 25 common-view data, after having applied a 3σ filtering. The standard deviation of the residuals computed for the link, in the case of the improved ionospheric corrections is slightly smaller (10%) than the customary one (2.5 ns).

The differences between the ionospheric delay corrections computed from the geodetic receiver data and those supplied by the timing receivers, for the same period, are better seen in Fig.5 which shows a peak-to-peak excursion of 2.1 ns and an average bias of –0.5 ns with a standard deviation of 0.6 ns. These results suggest that a further processing of the standard common-view synchronization data does not improve significantly the uncertainty of the comparisons but, from the detailed representation of one day of the two ensemble of ionospheric corrections data for each satellite used (Fig.6), it can be seen that the "modelled" one exhibits an overestimate of the correction (2 to 9 ns) at both sites, with maximum values around local noon. In Fig.7 the same information is reported for the whole period of the time comparisons. As only the satellite passages for which results from the two kind of receivers were available both in Torino and in San Fernando have been used for this investigation, the average number of data was 25, about 40% lower than the customary one utilized in time scale comparisons with GPS.

From what seen above, in the case of a user not operating its receiver in the common-view mode, the correction technique described in this paper can improve significantly the synchronization results. It must also be taken into account that this experiment has taken place in a period close to the minimum of solar activity and therefore some of the effects seen before can be even of more significance in the years to come.

CONCLUSIONS

An investigation on the improvement obtainable in time scales comparisons, performed with the common-view technique and the standard timing receivers, using ionospheric corrections computed from phases and pseudoranges measurements of dual-frequency GPS receivers, has been performed at IEN using the data available in RINEX files and relative to two Italian geodetic stations and the Observatory of San Fernando in Spain.

Both for the determination of the ionospheric corrections and the evaluation of the differential hardware delays, a new approach for which computer programs have been developed and tested experimentally at IEN and IROE has been adopted.

While the comparisons with the common-view technique between the time scales of IEN and ROA do not show to gain significantly from the use of the ionospheric corrections applied, at least in this period of small solar activity, it is evident that in the case of a one-way user, the experimented technique can bring an improvement over the synchronization data as given by the standard GPS receivers.

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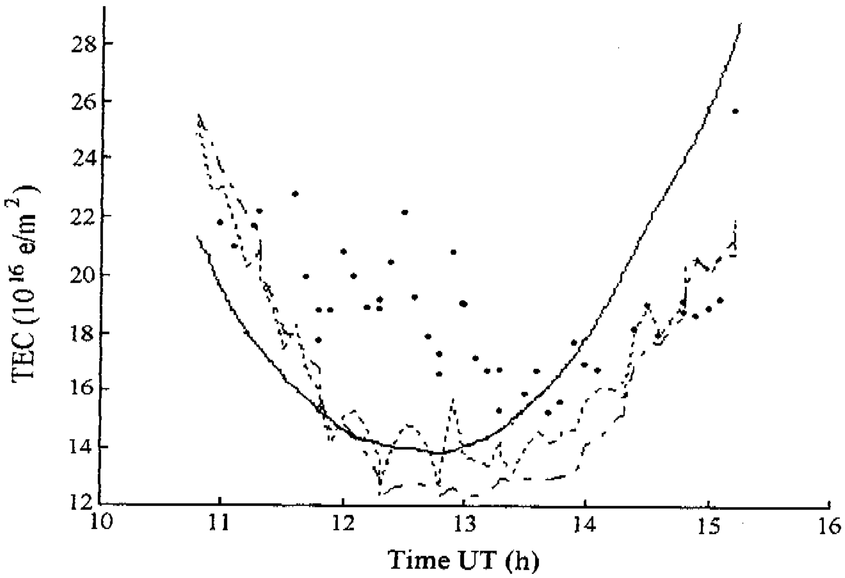

Fig. 1.a - Comparison between the data supplied by a dual-frequency GPS receiver and models for ionospheric corrections (PRN03, 1996-06-23).

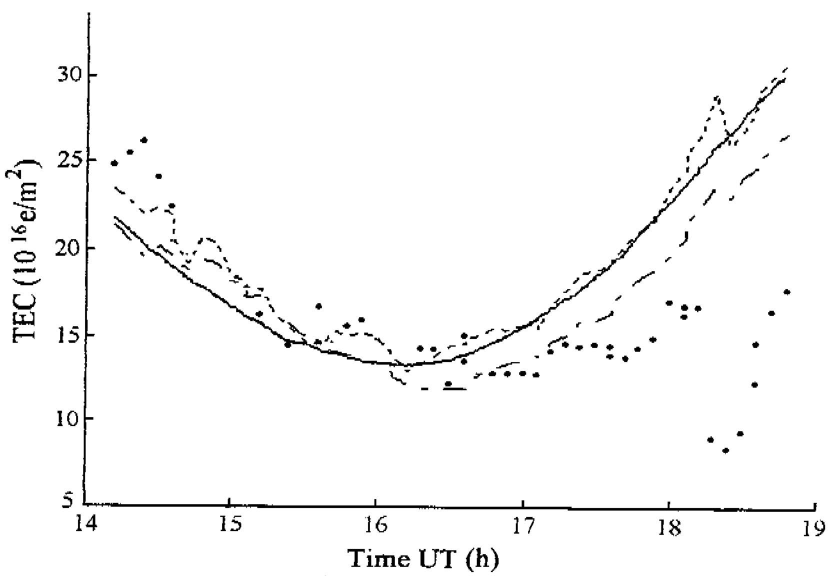

Fig. 1.b - Comparison between the data supplied by a dual-frequency GPS receiver and models for ionospheric corrections (PRN15, 1996-06-23).

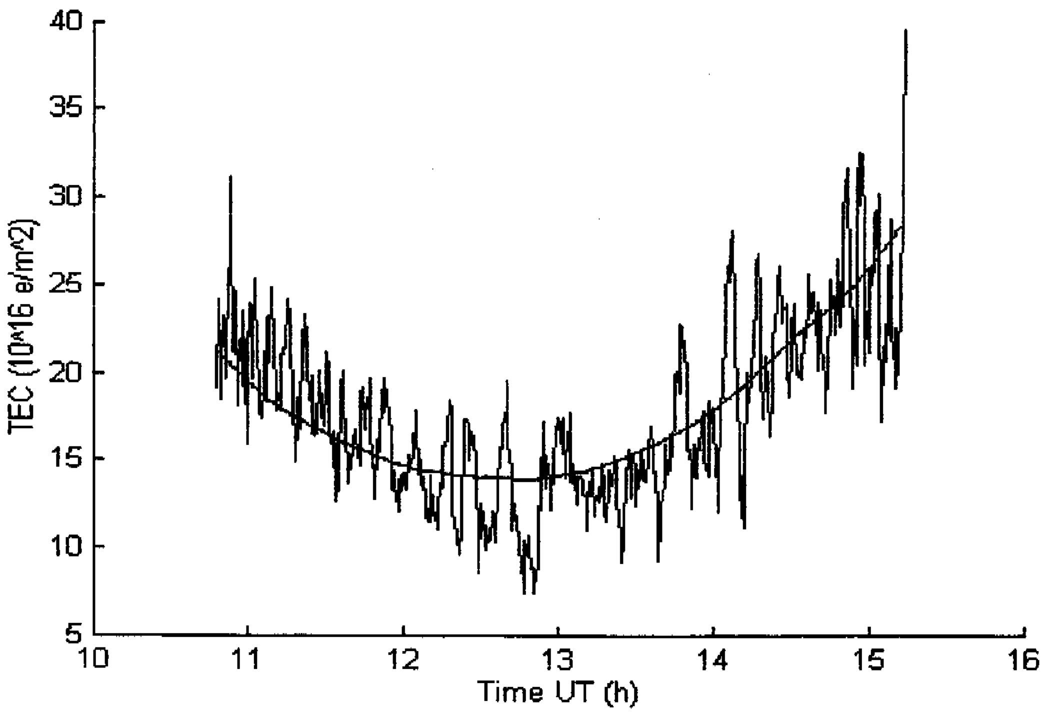

Fig. 2 - Ionospheric time delay (in *TEC* units) obtained from pseudoranges (segmented line) or computed at IEN.

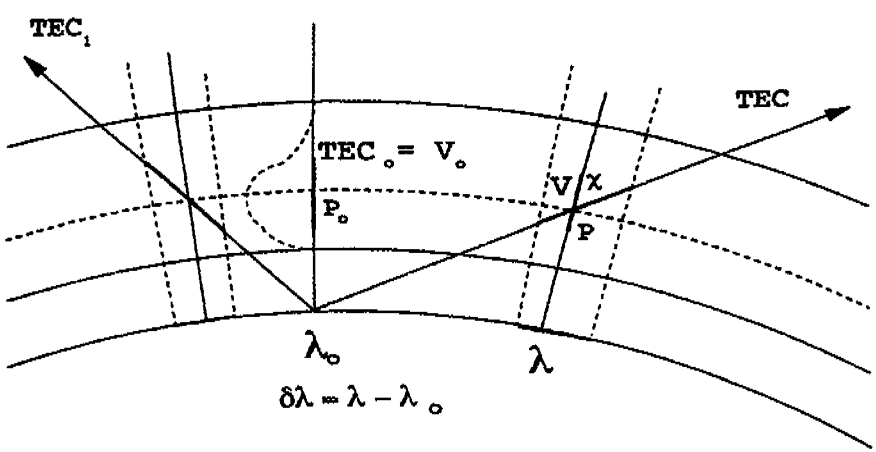

Fig. 3 -Representation of the relationship between the *TEC* in the satellite direction (slant) and the vertical one.

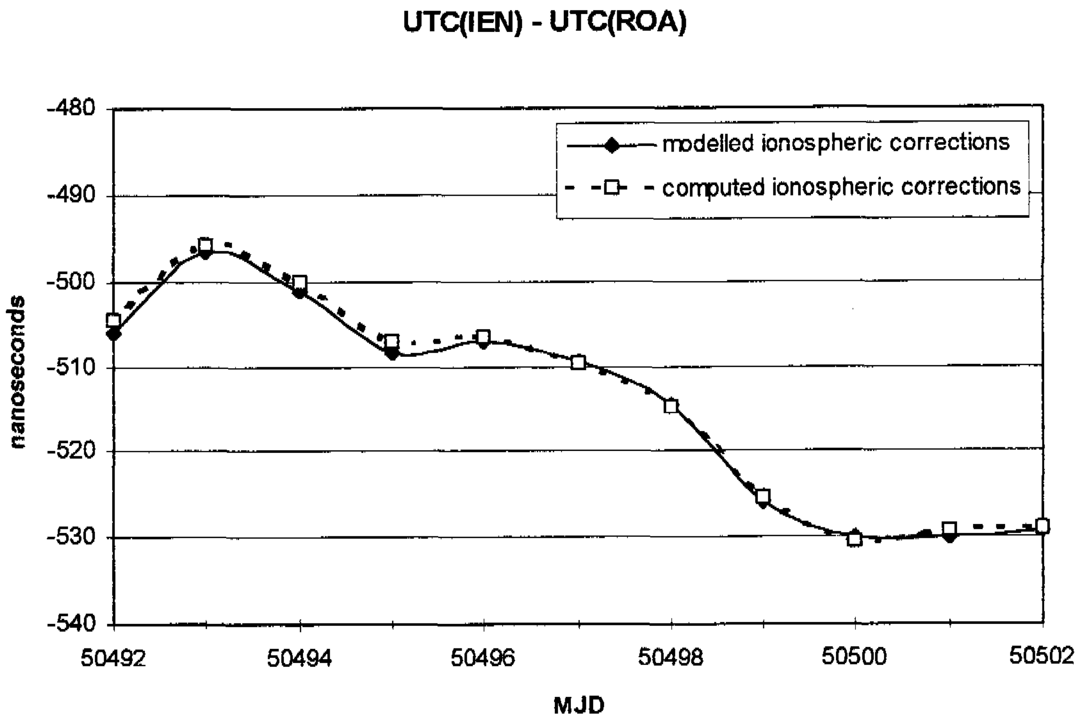

Fig. 4 - Time scales comparison using standard receiver output data or correcting for the ionospheric time delays.

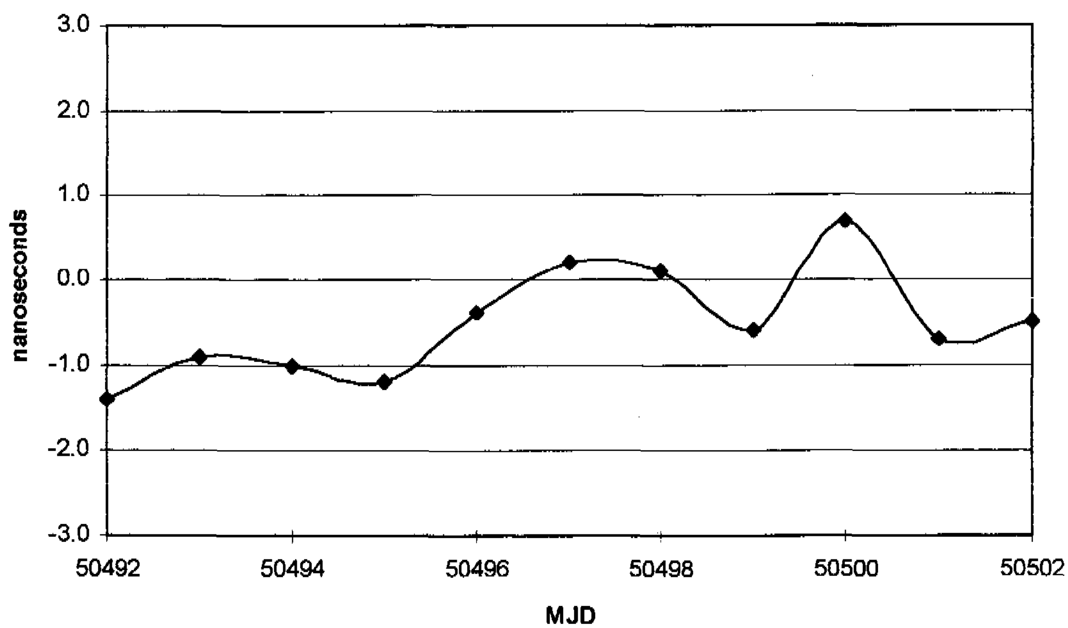

Fig. 5 - Differences between modelled and measured ionospheric corrections.

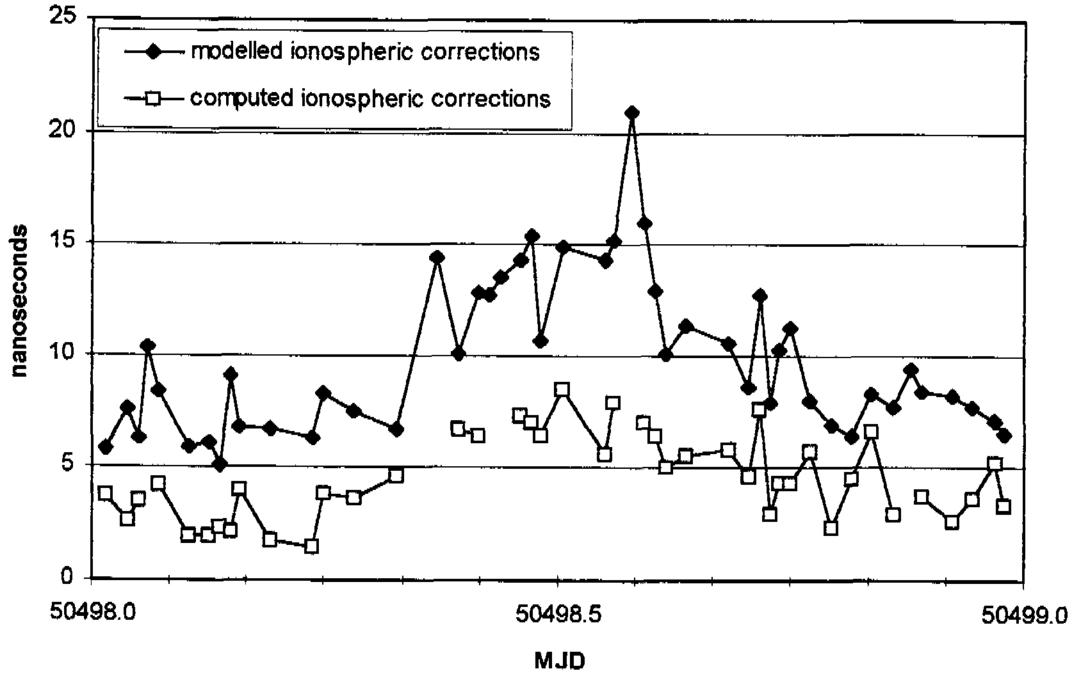

Fig. 6 - Modelled and measured ionospheric corrections for IEN-Torino (1997-02-19).

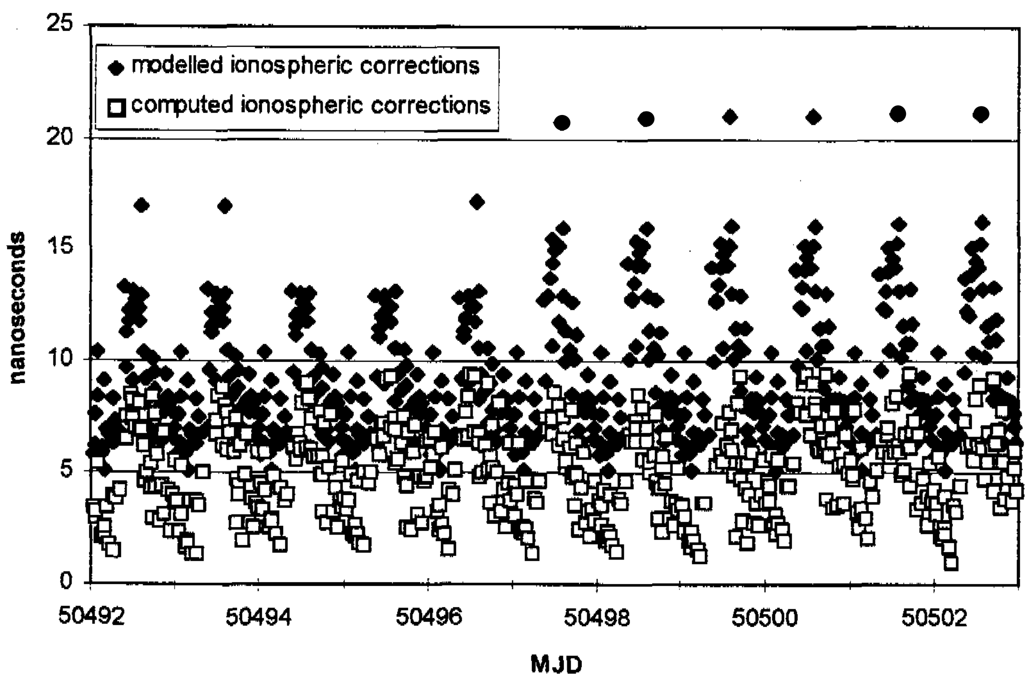

Fig. 7 - Modelled and measured ionospheric corrections for IEN-Torino (1997-02-13 to 1997-02-23).